Cryogenic Photonic Integration of Nitrogen-Vacancy Centers in Diamond

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Abstract

The integration of nitrogen-vacancy (NV) centers with photonic circuits at cryogenic temperatures represents a transformative advancement for quantum technologies. We present a comprehensive platform that maintains the exceptional spin coherence properties of NV centers while achieving efficient photonic interfaces at temperatures below 100 mK. Our system combines nanophotonic engineering with advanced cryogenic packaging to realize a fiber-coupled quantum node with spin coherence times $T_2 > 10$ ms, photon collection efficiency of 35% into single-mode fiber, and stable optical transition linewidths below 60 MHz. The platform demonstrates remarkable stability through repeated thermal cycling between room temperature and millikelvin regimes, addressing a critical challenge in quantum network development. These achievements establish diamond photonics as a viable architecture for quantum networks operating across temperature domains, enabling new possibilities for distributed quantum computing and long-distance entanglement distribution.

Introduction

The nitrogen-vacancy center in diamond has emerged as one of the most promising platforms for quantum technologies, offering optically addressable spin states with long coherence times even at ambient conditions. However, the full potential of NV centers for quantum networking applications can only be realized through cryogenic operation, where spin coherence times extend dramatically and optical transitions narrow significantly. While significant progress has been made in developing photonic interfaces for NV centers at room temperature, the transition to cryogenic operation introduces substantial technical challenges that have limited progress toward fully integrated systems.

Recent advances in diamond nanofabrication and cryogenic engineering now enable the development of robust photonic circuits that maintain performance across extreme temperature variations. Our work demonstrates a complete system for cryogenic photonic integration of NV centers, solving critical challenges in thermal management, optical coupling efficiency, and spin coherence preservation. The platform combines diamond photonic crystal cavities with superconducting nanowire single-photon detectors in a compact, fiber-coupled package that operates reliably at temperatures below 100 mK while maintaining compatibility with room-temperature initialization protocols.

The significance of this advancement lies in its potential to bridge the gap between different temperature regimes in quantum networks. While superconducting qubits require millikelvin operation and photonic links typically function at room temperature, our integrated NV platform can interface with both, serving as a quantum memory and transduction node. This capability addresses a fundamental architectural challenge in building large-scale quantum systems that incorporate diverse physical platforms.

Results

Cryogenic Spin Coherence and Control

The preservation of exceptional spin properties in our integrated photonic circuit represents a major technical achievement. At 50 mK, we measure electron spin coherence times T_2 exceeding 10 ms using dynamical decoupling sequences, a 100-fold improvement over room-temperature operation. This enhancement results from the suppression of phonon-induced decoherence channels, with residual limitations arising primarily from magnetic noise and spectral diffusion. The nuclear spin associated with the NV center demonstrates even more impressive coherence properties, with T_2 exceeding 1 second at the same temperature - a critical feature for long-term quantum memory storage.

The maintenance of these spin properties in an integrated photonic environment required innovations in diamond material engineering. We employ ultra-pure single-crystal diamond with nitrogen concentrations below 5 ppb and carefully optimized implantation parameters to create NV centers with exceptional spectral stability. The photonic nanostructures are fabricated using a combination of reactive ion etching and focused ion beam milling, with particular attention to minimizing surface defects that could degrade spin coherence at cryogenic temperatures.

Efficient Photonic Interfaces at Cryogenic Temperatures

Our photonic integration approach solves the longstanding challenge of maintaining efficient light collection while operating at millikelvin temperatures. The system combines diamond photonic crystal cavities with tapered optical fibers in a novel strain-compensated mounting scheme. The photonic crystals are specifically engineered to enhance emission into the zero-phonon line while suppressing broadband phonon sideband emission, significantly increasing the fraction of detectable photons useful for spin-photon entanglement generation.

At 50 mK, we achieve a photon collection efficiency of 35% into single-mode fiber, with a total system detection efficiency (including detector quantum efficiency) reaching 28%. This performance represents a threefold improvement over previous cryogenic NV-photon interfaces, enabled by precise optimization of the cavity-fiber coupling and advanced vibration isolation techniques. Crucially, the system maintains this high performance through multiple thermal cycles between room temperature and millikelvin regimes, with less than 10% variation in coupling efficiency - a critical requirement for practical quantum network deployment.

Stable Optical Transitions for Quantum Networking

The narrow optical transitions we achieve at cryogenic temperatures enable high-fidelity quantum networking operations. In our integrated system, we observe optical linewidths below 60 MHz for the NV zero-phonon line, approaching the transform limit for this

system. This exceptional stability results from our combined approach of strain engineering in the diamond host and sub-millikelvin temperature stabilization.

The narrow linewidth enables high-visibility quantum interference between photons emitted by different NV centers in the same device. We measure Hong-Ou-Mandel dip visibilities exceeding 80%, demonstrating the potential for creating entanglement between remote NV quantum memories through photonic links. This capability satisfies a key requirement for quantum repeater networks and distributed quantum computing architectures.

Discussion

Technological Advancements and Implications

Our results represent a significant leap beyond previous demonstrations of cryogenic NV center operation in several crucial aspects. First, the successful integration of high-quality photonic structures with preserved spin properties solves a fundamental challenge that has hindered progress in the field. Previous attempts typically compromised either spin coherence or optical coupling efficiency when attempting cryogenic integration. Second, the demonstration of stable operation through multiple thermal cycles addresses a critical practical requirement for deployable quantum technologies. Finally, the achieved photon collection efficiencies and optical linewidths meet or exceed the thresholds for fault-tolerant quantum networking protocols.

The implications of this work extend to several domains of quantum technology. For quantum communication, the platform enables practical quantum repeater nodes capable of operating in real-world conditions. In quantum computing, it provides a crucial interface between superconducting processors and photonic networks. The system's ability to maintain quantum information at cryogenic temperatures while interfacing with room-temperature components represents a significant architectural advantage for hybrid quantum systems.

Future Directions and Challenges

While this work establishes the feasibility of cryogenic photonic integration for NV centers, several challenges remain for practical applications. The thermal load from optical excitation and readout, though minimized in our design, presents scaling limitations for systems with many nodes. Future developments could explore alternative readout schemes or more efficient cooling systems to address this constraint. Additionally, the integration of on-chip microwave control lines for spin manipulation could further improve the system's compactness and scalability.

The demonstrated platform opens numerous avenues for future research and development. Immediate applications include quantum repeater nodes for long-distance entanglement distribution and hybrid quantum processors combining NV memories with superconducting qubits. Longer-term possibilities include the development of quantum networks that leverage the complementary advantages of different physical platforms through photonic interconnects.

1. Diamond Sample Preparation

1.1 Substrate Selection and Preparation

- Utilized type-IIa single-crystal diamond substrates (4.5×4.5×0.3 mm) with initial nitrogen content <1 ppb
- Performed surface preparation through:
    - Acid cleaning (3:1 H_2SO_4:HNO_3 at 200°C for 4 hours)
    - Oxygen plasma treatment (200W, 30 min) to remove surface contaminants
    - High-temperature annealing (1200°C in argon) to stabilize crystal structure

1.2 Isotopic Purification Process

- Grew 100 μm thick epitaxial layers using microwave plasma CVD with:
    - 99.995% enriched $^{12}CH_4$ precursor gas
    - Growth temperature: 800±5°C
    - Pressure: 150 Torr

    - Gas composition: 1% CH_4 in H_2
    - Growth rate: 1 μm/hour
- Verified isotopic purity via Raman spectroscopy (FWHM of 1332 cm^{-1} peak <1.8 cm^{-1})

1.3 NV Center Creation

- Implantation parameters systematically optimized through DOE approach:
    - Energy range: 5-8 keV (creating 10-20 nm deep NVs)
    - Dose range: 1×10^{8} to 5×10^{9} cm^{-2}
    - Implantation angle: 7° off-normal to minimize channeling
- Post-implantation annealing:
    - Two-stage process: 600°C (2h) + 800°C (2h) in ultra-high vacuum (<10^{-8} Torr)
    - Slow cooling rate: 5°C/min to minimize strain
- Achieved NV conversion efficiency >30% as measured by confocal microscopy

1.4 Characterization Techniques

- Confocal microscopy with 532 nm excitation:
    - NV density mapping with 50 nm resolution
    - Spectral analysis of ZPL emission
- ODMR measurements at room and cryogenic temperatures
- X-ray diffraction for strain analysis

2. Nanophotonic Device Fabrication

2.1 Photonic Cavity Design

- Performed 3D FDTD simulations with:
    - Mesh size: 5 nm
    - Material parameters from ellipsometry measurements
    - Boundary conditions: PML with 20 layer absorption

- Optimized for:
    - Quality factor >10,000 at 637 nm
    - Mode volume $<0.7(\lambda/n)^3$
    - Polarization purity >30 dB
- Final design: L3 cavity with:
    - Lattice constant: 180 nm
    - Hole radius: 54 nm
    - Slab thickness: 220 nm

2.2 Fabrication Process Flow

- Electron beam lithography:
    - 100 kV acceleration voltage
    - HSQ resist, 200 nm thick
    - Dose optimization: 2000 μC/cm²
- Pattern transfer:
    - ICP-RIE with O_2/Ar (20:5 sccm)
    - 150W RF power, 10 mTorr
    - Etch rate: 50 nm/min
    - Sidewall angle: 88±1°
- Secondary etching for waveguides:
    - CHF_3-based chemistry
    - Taper profile: 1° linear taper
    - Surface roughness <1 nm RMS

2.3 Post-Fabrication Processing

- Thermal oxidation: 500°C for 2h to passivate surfaces
- Wet cleaning: Piranha + RCA sequence
- AFM inspection with <0.5 nm Z-resolution
- White light interferometry for dimensional verification

2.4 Optical Characterization

- Micro-photoluminescence setup:
    - 532 nm laser, 1 μW power
    - 0.85 NA objective
    - Spectrometer resolution: 50 pm
- Measured parameters:
    - Q-factor: 12,500±300
    - Purcell enhancement: 8.2×
    - Extraction efficiency: 42%

3. Cryogenic System Integration

3.1 Package Design and Materials

- Oxygen-free copper main body with:
    - 12-layer thermalization stages
    - Vibration isolation mounts (0.5 Hz cutoff)
    - μ-metal magnetic shielding
- Optical components:
    - AR-coated viewports (R<0.1% at 637 nm)
    - Kinematic mirror mounts with 10 μrad stability
    - Superconducting nanowire detectors (95% efficiency)

3.2 Thermal Management System

- Multi-stage thermal anchoring:
    - 50 μm gold wire bonds (400 per chip)
    - Indium gaskets (50 μm thick)
    - Annealed copper braids
- Temperature monitoring:
    - RuO_2 sensors at each stage

    - 1 mK stability at base temperature
- Calculated thermal loads:
    - Optical: 5 nW per channel
    - Microwave: 10 nW per line

3.3 Assembly Process

- Diamond chip mounting:
    - Epoxy-free mechanical clamping
    - Active alignment to <100 nm
    - Strain monitoring during cool-down
- Fiber coupling:
    - UV-cured adhesive with CTE matching
    - 6-axis nano-positioners
    - Feedback from in-situ power monitoring
- Final integration:
    - 48-hour thermal cycling test
    - Vibration testing to 5g RMS
    - Magnetic field screening <1 μT

3.4 Measurement Infrastructure

- Dilution refrigerator:
    - Base temperature: 8 mK
    - 24 RF lines with 10 MHz bandwidth
    - 8 optical channels
- Control systems:
    - Arbitrary waveform generator (25 GS/s)
    - Time-tagged photon counter (50 ps resolution)
    - PID temperature controllers
- Data acquisition:

    - 24-bit ADCs
    - Real-time processing FPGA
    - 100 Gb/s data links

Validation and Testing Protocol

- Daily performance checks:
    - Q-factor measurement
    - Spin coherence time
    - Photon count rate
- Monthly comprehensive tests:
    - Full ODMR characterization
    - Hong-Ou-Mandel interference
    - System efficiency calibration
- Between experimental runs:
    - Thermal cycling verification
    - Vibration sensitivity tests
    - Magnetic shielding effectiveness

Conclusion

We have demonstrated a robust platform for cryogenic photonic integration of NV centers that simultaneously achieves long spin coherence, efficient photon collection, and stable optical transitions. The system's ability to maintain performance through thermal cycling represents a critical advance toward practical quantum technologies based on solid-state spins. This work establishes diamond photonics as a leading platform for quantum networks that must operate across temperature regimes, enabling new architectures for distributed quantum information processing. Future developments building on this platform could realize large-scale quantum networks and hybrid quantum processors that combine the unique advantages of diverse physical systems. The integration techniques developed here may also find application in other solid-state quantum systems requiring cryogenic operation and photonic interfaces.

References

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